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OPTICAL INTERFEROMETERS FOR TESTS OF RELATIVISTIC GRAVITY IN SPACE

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I. INTRODUCTION

We consider a space-based astrometric interferometer with a large optical bandwidth. POINTS (Precision Optical INTerferometry in Space) would measure the angular separation of two stars separated by about 90 deg on the sky with a nominal measurement error of 5 microarcseconds (μas). For a pair of mag 10 stars, the observation would require about 10 minutes. We estimate the instrument would measure daily the separation of two stars for each of about 60 pairs of stars; a random sequence of such measurements, if suitably redundant, contains the closure information necessary to detect and correct time-dependent measurement biases to well below the nominal measurement accuracy. The 90 deg target separation permits absolute parallax measurements in all directions.

A redundant observing schedule for 300 stars and 5 quasars (1,500 star-star observations and 250 star-quasar observations) would provide extra redundancy to compensate for the quasars' higher magnitude. If a nominal 30-day observation sequence were repeated 4 times per year for 10 years, we would obtain means stellar parameter uncertainties of: 0.6 μas, position; 0.4 μas/y, proper motion; and 0.4 μas, parallax (Reasenberg 1986). This set of well-observed stars and quasars would form a "rigid frame" and the stars would serve as reference objects for measurements of all additional targets, as well as being targets of direct scientific interest.

In the following sections we consider the instrument global data analysis science objectives including a relativity test and technology. A compressed version of the VuGraphs shown follows the text.

II. INSTRUMENT

The POINTS instrument comprises two starlight interferometers and a metrology system. Each interferometer has a baseline 2 m long, and 2 afocal telescopes, each with a primary mirror 25 cm in diameter. The axes of the interferometers are separated by an angle $\varphi = \varphi_o + \Delta$, where φ_o is 90° and $|\Delta|$, the absolute value of the articulation angle, is less than 3. The instrument determines θ (≈ 90 deg), the angular separation between two stars, by measuring φ and, independently, δ_1 and δ_2, the offsets of the target stars from their respective interferometer axes. Once a target star is in the field of an interferometer, the corresponding δ is measured through the analysis of the dispersed fringe which forms a "channelled spectrum." The use of this technique simplifies the instrument by making the fringe easy to see; it eases the pointing requirements to about ± 3 arcsecond. The nominal limiting magnitude is 17, but depends on the level of disturbance that the instrument suffers. Techniques exist to extend the limiting magnitude by five, provided detector noise does not dominate. Central to the design is the real-time metrology of (1) the angle between the interferometers, and (2) the starlight optical path; each of these metrology systems uses a laser interferometer scheme based on technology that is either currently available or under development and expected to be available soon.

The control of systematic error is the key to achieving the nominal accuracy of 5 μas. We address this problem at three levels: (1) stable materials, structural design, and thermal control; (2) real-time metrology; and (3) the detection and correction of systematic error in conjunction with the global data analysis. For a 2-m baseline, the nominal 5-μas uncertainty corresponds to a displacement of 1 end of the interferometer toward the source by 50 picometers (pm). (See Table 1.) Since similar displacements of internal optical elements are also important, the instruments require real-time metrology of the entire starlight optical path accurate to a few pm. This metrology does not pose an overwhelming problem because (1) the precision is needed only for a narrow bandwidth ($\approx 10^{-3}$ Hz, since higher frequency errors will tend to average out during a single star-pair observation), and (2) a slowly changing bias in the measurement is acceptable, as discussed below.

TABLE 1

PRELIMINARY POINTS ERROR BUDGET OF 50 PM*

I.	Starlight determination of δ_1 and δ_2		43 pm	
	A.	Photon statistics		40 pm
	B.	Detector		10 pm
	C.	Suboptimal estimator and loss of fringe tracking		10 pm
II.	Metrology determination of ø		20 pm	
	A.	FAM		10 pm
	B.	Laser gauges		10 pm
	C.	Fiducial blocks		10 pm
	D.	Lasers		10 pm
III.	Modeling errors		10 pm	
	A.	Structure (including vibration)		
	B.	Ephemeris error		
	C.	Geometry		

*(5mas * 2.5 ¥ 10^{-11} radians) ¥ 2 m = 50 ¥ 10^{-12} m ∫ 50 pm.

The angle, φ, between the baselines of the two interferometers is determined by measuring the six distances among four fiducial blocks in the system. Each of the six distances is measured by a laser gauge which must meet the following requirements: (1) precision of a few pm; (2) measurement accuracy not sensitive to small changes in distance (*i.e.*, not a null device and free of bias periodic in distance); (3) ability to keep track of significant distance changes (*i.e.*, many wavelengths); and (4) ability to operate without the calibration that would be made possible by making multiwavelength changes in the distance measured. We are developing such a laser gauge (Phillips and Reasenberg 1988) and suitable solid-state sources are expected in the next few years. "Full-Aperture Metrology" (FAM) surveys the optical components that transfer the starlight from the primary mirrors to the beamsplitter in each stellar interferometer. FAM provides three significant advantages over conventional approaches.

(1) FAM removes complexity. The usual metrology systems use a large number of laser gauges to determine the locations of the elements individually. From these measurements, the optical path through the system is computed. FAM directly measures the optical path through the system.

(2) FAM measures the correct quantity. Because the metrology signal fully illuminates the surface of each optical element that determines the starlight phase at the beamsplitter, the phase of the metrology signal is representative of the average starlight path through the system.

(3) FAM provides the basis for an operational definition of the direction of the interferometer baseline. It results in a pair of "fiducial points" located in the "fiducial blocks" in front of each interferometer. These fiducial points, which lie on lines parallel to (or held at fixed small angles to) the interferometer baselines, are used to determine φ, the angle between the two interferometers' optical axes.

Each fiducial block is a collection of optical elements which joins the ends of the metrology paths.

III. GLOBAL DATA ANALYSIS

When an observation set has sufficient redundancy, it can be analyzed to yield a rigid frame; it serves to determine the angular separation of all pairs of observed stars. The redundancy is measured by M, the ratio of the number of observations to the number of stars observed. With moderate redundancy, M = 4.2, the uncertainty in the separation of any two stars (including those not simultaneously observed) is about equal (on average) to the instrument measurement uncertainty. The star grid is free of regional biases and may be further strengthened by additional data obtained when the grid stars are used as reference stars for additional science targets.

The metrology system that is described above is capable of providing the required precision, but contains finite-sized optical components, each of which will introduce a bias into the measurement of the angle. This bias will surely be time-dependent at the microarcsec level. Both the determination and correction of that bias naturally occur when the observations are combined in a least-squares estimate of the individual stellar coordinates (including proper motion and parallax), the instrument model parameters, and the expected biases. In particular, our covariance studies have shown that, even without the introduction of a special observing sequence, it is possible to estimate simultaneously the stellar coordinates and several instrument bias parameters per day without significantly degrading the stellar coordinate estimates. Thus, we have latitude in the instrument design: metrology biases and related errors can be allowed to change on a time scale of hours without significantly degrading the performance of the instrument. The covariance studies also show that the baseline lengths, systematic errors in φ, and other instrument parameters are naturally determined in the data analysis.

IV. SCIENCE

A discussion of some astrophysical applications of POINTS is given by Reasenberg *et al.* (1988) and in less detail by Reasenberg (1984). These applications include (1) a light-deflection test of general relativity, perhaps to second order in the solar potential, but 10^3 times more accurate than the present best test (Fomalont and Sramek 1977); (2) a search for other planetary systems, which will either find such systems or show that they are considerably less common than is now projected; (3) development of a distance scale based on direct parallax determinations for a large number of Cepheids; (4) a determination of the masses of stars in binary systems and those close enough to apply the method of perspective acceleration; (5) parallax measurements yielding both absolute stellar magnitudes and, in conjunction with mass estimates and other data, a sharpened mass-color-luminosity relation; (6) a vastly improved global reference frame and a tie to existing ones; (7) a refinement of our knowledge of the mass distribution in the Galaxy; (8) a strictly geometric (*i.e.*, coordinate and parallax) determination of the membership of star clusters; and (9) a bound on, or a measurement of, quasar proper motions. In addition, there are applications to solar-system studies and to the navigation of spacecraft, particularly in the outer solar system.

We have performed a series of covariance studies of a POINTS light-deflection test using a common set of 100 Monte Carlo stars which includes ten constrained to be within 0.2 deg of the ecliptic. Over a 2-year experiment, quarterly observations were made of all pairs simultaneously observable with Δ chosen to yield M = 5. Whenever one of the 10 "special stars" was between L_G (glare limit) and L_P (pre-emptive limit), it was observed continuously, cycling among the stars within Δ of 90 deg of it. On any day when one of the special stars was between L_P and L_D (daily survey limit), it was observed once with each other star within Δ of 90 deg from it.

For each star (except for the two held fixed to prevent degeneracy) we estimated five parameters: location (2), proper motion (2), and parallax. Along with the 492 star parameters, we simultaneously estimated 4 relativistic-solar parameters: γ (PPN coefficient), Λ (second-order coefficient), J_2 (solar quadrupole coefficient), and l (solar angular momentum). [See Epstein and Shapiro (1980) for a discussion of these four parameters and the deflection to second order.] The results are shown in Table 2.

We conclude that a POINTS mission could improve the first-order test 2 to 3 orders of magnitude beyond the present uncertainty of 0.002 for γ, but that it would yield only a marginal result for Λ with the instrument's present nominal specifications. There are, however, several factors in the specifications that could be altered to change the sensitivity in either direction. For example, the 5-μas nominal measurement uncertainty could be improved by choosing bright target stars, increasing the photon detection probability from its nominal 2%, expanding the baselines, or enlarging the primary mirrors. The instrument's metrology system would have to be improved correspondingly. On the other hand, the solar glare limit, L_G, is undoubtedly the single most critical factor in the second-order test, as expected, since the second-order deflection varies as the inverse-square of the impact parameter. Note especially the dramatic decrease in $\sigma(\Delta)$ that comes from decreasing L_G to 0.25 deg (limb grazing) and, by contrast, the lack of improvement from extending L_D to 8 deg.

TABLE 2

COVARIANCE STUDY FOR ESTIMATION OF RELATIVITY PARAMETERS

OBSERVATION PROGRAMS FOR COVARIANCE STUDY

PARAMETER	SPECIFICATIONS				
Solar glare limit (L_G deg)*	0.5	0.25	0.5	0.75	.0
Pre-empt limit (L_P deg)	1.0	0.75	1.0	1.25	1.5
Daily survey limit (L_D deg)	8	4	4	4	4
Total observations	7293	6104	5996	5901	5846

COVARIANCE STUDY RESULTS

MODEL PARAMETER	NOMINAL VALUE	UNCERTAINTY (STANDARD DEVIATION)				
$\gamma\,(10^{-6})$	10^6	2.2	1.2	2.4	3.7	5.1
Λ	1.0	2.2	0.5	2.4	5.8	11
$J_2\,(10^{-6})$†	0.1	4.4	0.4	4.5	17	43
$l\,(10^{-6})$†	0.5	0.9	0.3	1.0	2.2	3.7

*L_D is taken as an effective limit representing the gradual degradation of the instrument performance as the sun-target angle is decreased. All three limits are in degrees from the center of the sun.

†The "dimensionless" quantities J_2 and l are, respectively, the quadrupole moment and the angular momentum of the Sun in units of solar mass and radius and the speed of light. The nominals are based on the standard model of the central condensation of the sun and the assumption that the spin rate is uniform.

V. TECHNOLOGY

None of the technology thus far identified as being required for POINTS is far beyond the present state of the art. For the most challenging problem, the internal metrology, we have solutions in principle. However, these do require a continuation of our ongoing development at CFA. Some of the required technologies are developing rapidly for reasons unrelated to POINTS. A list of the most important technology areas is given in Table 3. Note that these technologies are not peculiar to POINTS, but will have broad application to advanced space instrumentation.

TABLE 3

POINTS TECHNOLOGY CHALLENGES

Space qualified zone-plate mirror
Fabrication of fiducial blocks
Laser gauges
Photon-counting detectors of high efficiency and long life — space qualified
Microdynamics of the optical bench
Pointing and isolation (especially if instrument is on Space Station)
Computation at spacecraft

The technology to be demonstrated in the POINTS program will have a fundamental impact on the development of future optical interferometers for placement in space. In particular, we believe that the application of laser metrology to measure critical optical path lengths and instrument geometry would simplify the design of at least three classes of future interferometric instruments:

(1) "Not-quite-imaging" devices are generally linear arrays of two or more apertures which, in some cases, are made movable. They provide an incomplete sample of the so-called u-v plane. However, such information is useful for learning about the target when it has a strong symmetry, but is hard to resolve.

(2) Fully imaging interferometric devices are discussed extensively in a report prepared by Perkin-Elmer for NASA-Marshall (Final Study Report for Astronomical Interferometric Systems Technology Requirements [AISTR], Revision A, May 1986, NASA Contract #NAS8-26105, P-E# ER991A, and available from Mr. Max Nein at NASA-Marshall), as well as in the proceedings of the Workshop on High Angular Resolution Optical Interferometry from Space (BAAS, 16(3,II), 1984), in the proceedings of the Colloquium on Kilometric Optical Arrays in Space (ESA, SP-226, 1984), and in the Final Report of the Cambridge Workshop on Imaging Interferometry (March 1987, Battelle, Columbus, Ohio, supported by NASA-Astrophysics, D. Mouvard, Ed.).

VI. DISCUSSION

It is now widely recognized that interferometric instruments will play a major role in many aspects of space-based optical astronomy. (See, for example, the three volumes cited in the preceding paragraph.) Results of major importance will come from imaging interferometers with higher resolution and more light-gathering power than the Hubble Space Telescope (HST). However, such instruments must be large to achieve their advantage over existing instruments. POINTS, which is small, could perform a significant test of general relativity, open new areas of astrophysical research, and change the nature of the questions being asked in some old areas. It could be the first of a new class of powerful instruments in space and could prove the technology for the larger members of that class to follow.

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DISCUSSION

FAIRBANK: How accurately could you measure the proper motion Rigel?

REASENBERG: If Rigel were included as one of the grid stars, then after a ten-year mission we would know its proper motion with an uncertainty of under 0.5 microarcseconds per year. Even a few observations made within the first two years of a mission would yield proper motion for Rigel uncertain by less than 5 microarcseconds per year. In short, we could easily exceed the needs of GP-B. As a matter of scientific priority, I would expect that a highly redundant and robust observing schedule would be selected for Rigel.

HELLINGS: It seems like several systematic errors (such as thermal effects driven by the Sun) would have signatures identical to the relativity deflection you want to measure. How would you estimate such a bias?

REASENBERG: Although a solar-driven thermal bias is unlikely to look identical to the relativity effect, it may have a sufficiently similar signature to be a problem. To first order, the effect of instrument heating caused, for example, by looking at a target near the sun should be corrected by the Full-Aperture Metrology system. However, at some level this correction will fail. Pre-launch tests should tell us the characteristics of the failure and these characteristics should be confirmed by experiment in an early phase of the mission. For example, we might point the instrument to a bright pair of stars away from the Sun, measure their separation, then briefly swing the instruments so as to expose one of the interferometers to excessive heating. Finally, by pointing back to the bright pair, we could watch the decay of the residual distortion due to solar heating. When we better understand the failure mechanisms and characteristics for the FAM system, we will be able to devise more highly targeted post-launch tests.

TREUHAFT: To what extent do star or quasar structure fluctuations contribute to reference frame instabilities at the microarcsecond level?

REESENBERG: I know of no basis for discussing quasar structural fluctuations at the microarcsecond level. However, for stars much is known. I believe that for active stars, star spots can shift the center of light of a star by as much as a few percent of the stellar radius. However, most stars are not nearly so active, and the center of light shift should be well under one percent of the radius. One percent of a solar radius is a microacrsecond at 45 parsecs.

SCHUMAKER: How is your precision hurt by the nonpointlike nature of a target? For example, what about the probably large number of binaries that are undetected, especially those that are indistinguishable spectroscopically and comparable to each other in brightness?

REESENBERG: It is inevitable that some of our selected targets will be undetected binaries and we therefore have investigated the response of POINTS to such a target. When the two sources are close together compared to the fringe spacing (50 mas), the instrument treats the source as if it were at the center of light. For sources of different temperatures and either similar or dissimilar magnitudes, the instrument can determine the angular separation between the sources with almost the same precision as the position of the fainter source alone would have been determined, provided only that the binary nature of the source has been discovered. In this case, virtually no confusion results in the astrometric measurement. For an undetected companion, of the same temperature and at least one magnitude fainter than the target star, there is a measurement bias which is zero mean, periodic in the star-companion separation, and proportional to the ratio of the brightness of the companion to the brightness of the target. The envelope of the bias can be made to fall as the cube of the target-companion separation, dropping below 1 microarcsecond at less than an arcsecond separation for a companion one magnitude fainter than the target.